08:50:55 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 01/12/94

Active

Project #: E-20-601 Cost share #: E-20-312 Rev #: 9
Center # : 10/24-6-R6874-0A0 Center shr #: 10/24-6-F6874-0A0 OCA file #:
Work type : RES
Contract#: CTS-8915537 Mod #: BR DTD 940105 Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : Y CFDA: 47.041
Main project #: PE #: N/A

Project unit: CIVIL ENGR Unit code: 02.010.116
Project director(s):
ROBERTS P J W CIVIL ENGR (404)894-2219

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 891215 to 941130 (performance) 941130 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	252,973.00
Funded	0.00	252,973.00
Cost sharing amount		71,838.00

Does subcontracting plan apply ?: N

Title: ENERGETICS OF JET AND PLUME TURBULENCE IN STRATIFIED FLUIDS

PROJECT ADMINISTRATION DATA

OCA contact: Jacquelyn L. Tyndall 894-4820

Sponsor technical contact

STEPHEN C. TRAUGOTT
(202)357-9606

NATIONAL SCIENCE FOUNDATION
1800 G STREET, N.W.
WASHINGTON, D.C. 20550

Sponsor issuing office

ANDREA R. KLINE
(202)357-9626

NATIONAL SCIENCE FOUNDATION
1800 G STREET, N.W.
WASHINGTON, D.C. 20550

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A NSF supplemental sheet
Equipment title vests with: Sponsor GIT X

Administrative comments -
ISSUED TO INCORPORATE BUDGET REVISION DATED 1-5-94 SHIFTING FUNDS BETWEEN BUDGET CATEGORIES. NSF AMENDMENT 6 EXTENDS PROJECT TERM DATE TO 11/30/94.

08:50:55 SUBPROJECTS OF MAIN PROJECT E-20-601 01/12/94

Project number	Spon/Div	Project Director	Total Contract	Project Unit	Total Funded
E-20-667	107/000	ROBERTS P J W	10,900.00	CIVIL ENGR	10,900.00

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 06/14/95

Project No. E-20-601

Center No. 10/24-6-R6874-0A0

Project Director ROBERTS P J W

School/Lab CIVIL ENGR

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. CTS-8915537

Contract Entity GTRC

Prime Contract No.

Title ENERGETICS OF JET AND PLUME TURBULENCE IN STRATIFIED FLUIDS

Effective Completion Date 941130 (Performance) 941130 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	N	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments
LETTER OF CREDIT APPLIES. 98A SATISFIES PATENT REQUIREMENT.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT (SUBPROJECTS)

Closeout Notice Date 06/14/95

Project No. E-20-601 Center No. 10/24-6-R6874-0A0_

Project Director ROBERTS P J W____________ School/Lab CIVIL ENGR_____

Sponsor NATL SCIENCE FOUNDATION/GENERAL______________________________

Project # E-20-667	PD ROBERTS P J W	Unit 02.010.116	T
GRANT # CTS-8915537	MOD#	ADM. REVISION CIVIL ENGR	*
Ctr # 10/24-6-R6874-0A1	Main proj # E-20-601	OCA CO JLB	
Sponsor-NATL SCIENCE FOUNDAT	/GENERAL	107/000	
ENERGETICS OF JET AN			
Start 891215 End 941130	Funded 10,900.00	Contract 10,900.00	

LEGEND
1. * indicates the project is a subproject.
2. I indicates the project is active and being updated.
3. A indicates the project is currently active.
4. T indicates the project has been terminated.
5. R indicates a terminated project that is being modified.

-601

Progress Report Number 1

Energetics of Jet and Plume Turbulence in Stratified Fluids

Project No. CBT-8915537

Period Covered: 12/15/89 to 12/14/90

by

Philip J. W. Roberts
School of Civil Engineering
Georgia Institute of Technology

The research project is an experimental study of the dynamics of collapse of jet- and plume-induced turbulence under the influence of density stratification. We have completely refurbished the experimental facility. This involved moving the test tank from our old Hydraulics Laboratory to the new, and aligning, cleaning, and repainting it. In addition, we have built a new plumbing system comprising water filters, pumps, flow meters, and mixing tanks and a diffuser for filling and stratifying the test tank. The filters are necessary to dechlorinate the water for the fluorescence measurements and to remove large particulates to enhance the quality of the scattered light for the laser anemometer. This new system will make it very easy to repeatedly fill the tank with an arbitrary stratification profile of the salt and ethanol solutions. A separate part of the plumbing system provides filtered cooling water for the Argon ion laser. This system is now fully operational.

Evaluation of fiber-optic Laser Doppler Anemometer systems has proceeded more slowly than expected. We are awaiting a final system demonstration in two weeks, at which time a decision on the system to purchase will be made. We anticipate delivery of the system early in the new year. This delay has been beneficial, however, as new frequency domain signal processors are now moving onto the market which appear to be much better suited to our application than the traditional counter, tracker, or covariance type processors. Frequency domain processors are more sophisticated than these older types, and behave better in an environment with a low signal-to-noise ratio, such as we are expecting in our stratified flows. It appears that we will be able to procure a frequency domain processor for a cost comparable to that which was expected for the older type processor.

Conversely, progress in flow-imaging has proceeded faster than expected and we have successfully obtained laser induced fluorescence images of non buoyant jets. To do this, the beam from a five Watt Argon Ion laser is converted to a thin sheet by passing it through cylindrical lenses. The sheet is directed into the flow field to which a fluorescent dye, Rhodamine 6G, has been added. We have found that very small dye concentrations, of the order of a few parts per billion, are needed for emission of light of sufficient intensity to measure. The fluoresced light which is emitted is captured by a gray scale video camera. Although we can and do digitize individual frames using a frame grabber, we do not have the capability to record the digitized images in real time in the laboratory. Instead, we record the analog signal on a 3/4 inch video tape recorder. The tape is then taken to another location on campus where the recorded images are digitized on an Abacus A20 video digitizer and stored in real time (30 frames per second) on an Abacus A60 which has the capacity to store 750 digitized frames (600 megabytes). We then transmit the digitized images over the campus fiber optic network for processing on Silicone Graphics workstations in the Civil

Engineering Department.

It was originally proposed to use these techniques for flow visualization only, as we believed that obtaining quantitative information was beyond our capabilities. We have found, however, that we can readily expand this flow imaging to obtain detailed statistics of tracer concentration fluctuations and mean concentration fields. This has required calibration of the system to account for the spatially varying laser light intensity, the laser sheet geometry, attenuation of the beam, the optics collection efficiency, and the characteristics of the analog recording and digitizing processes. We are doing this by varying the laser intensity and adding known dye amounts to obtain uniform dye concentrations in the test tank and in a smaller tank placed inside the larger test tank.

After extraction of the statistics of the concentration fluctuations and computation of time-averaged values, further image processing is done. The raw light intensities are converted to instantaneous dye concentrations. We have converted these dye concentrations to false colors which are much more readily interpreted by the eye than gray scales. We plan next to transfer these false color digital images back over the network to the Abacus A60. The RGB output of the A60 will then be transmitted to a Bosch 2000 encoder for combination with an NTSC sync signal to make false color videos and prints. The unusually large storage capacity of the Abacus and the large memory of our Silicone Graphics workstations (8 megabytes) make these manipulations possible. These techniques should afford considerable insight into the dynamical phenomena under study.

The image processing and software development has been the responsibility of Adrian Ferrier. Adrian began working on this project as an undergraduate this summer with support from the Research Experience for Undergraduates (REU) program. He is now continuing with this project for his Master's Thesis in our Computer Graphics group at Georgia Tech with a minor in mathematics.

In addition to flow imaging, we plan to use the laser induced fluorescence technique to obtain direct measurements of the turbulent flux of tracer, $\overline{u'c'}$. This will be done by simultaneously measuring velocity with the LDA and tracer concentration with the fluoresced light. We are exploring the possibility of using the same fiber-optic probe to capture the fluoresced light and the scattered light for the LDA measurements. The advantage of this technique is that the same optical path is used for the LDA and LIF, guaranteeing that the measurements are made simultaneously and at the same point.

Early in the new year two PhD students will begin working on some of the fluid mechanical aspects of this project. We expect that the rate of progress will then quicken considerably.

The next steps will be to complete calibration of the imaging system and begin detailed studies with the LDA. The flow we initially plan to study is a non-buoyant jet in a homogeneous environment. Of course, this flow has already been well-studied so it makes a good test system for verification of the new experimental techniques and for gaining experience with the LDA system.

Following demonstration of the experimental techniques we shall proceed to studies of buoyant jets into stratified and homogeneous environments. The fluids will be solutions of salt, ethanol, and water with the solute concentrations chosen so that the refractive index of the mixtures are constant. We have obtained the supplies for this (800 lb of salt, 55 gallons of denatured ethanol), and prior to performing the experiments we will carefully evaluate the density and refractive index of various solutions to choose the solute concentrations needed. Densities will be measured with a Troemner specific gravity balance we have recently acquired and which is capable of measuring density to a precision of 0.1 σ_t-units. Refractive index will be measured with a Brice-Phoenix Differential refractometer in the Chemistry Department. This instrument measures differences in refractive index with a precision of 0.00001. Having chosen the appropriate fluid compositions, we will then begin the studies of these buoyancy modified flows to investigate the flow dynamics and conditions leading to turbulence collapse under the influence of stratification as outlined in the original proposal.

Progress Report Number 2

Energetics of Jet and Plume Turbulence in Stratified Fluids

Project No. CBT-8915537

Period Covered: 12/15/90 to 12/14/91

by

Philip J. W. Roberts
School of Civil Engineering
Georgia Institute of Technology

The research project is an experimental study of the dynamics of collapse of jet- and plume-induced turbulence under the influence of density stratification. New instrumentation is being developed, including the use of laser-induced fluorescence (LIF) for mapping the tracer concentration field and flow visualization, and fiber-optic Laser Doppler anemometry combined with LIF for velocity and tracer flux measurements.

Most of the activity over the past year has been devoted to developing and calibrating our new image processing system. The images are obtained by capturing the light emitted by laser-induced fluorescence with a gray scale video camera. The beam from a five Watt Argon Ion laser is converted to a thin collimated sheet by passing it through cylindrical lenses and then directed into the flow field to which a fluorescent dye, Rhodamine 6G, has been added. A long pass filter allows only the fluoresced light to pass and removes the scattered light; we have found that very small dye concentrations, of the order of a few parts per billion, are needed for emission of light of sufficient intensity to measure. Previously, we had been recording images on 3/4" video tape, then taking the tape to be digitized, transmitting the digitized images over the campus network, and finally processing them on a Silicon Graphics Workstation. While this method allowed many frames to be digitized and stored, it proved to be somewhat unwieldy. We now have a complete image processing system, which allows digitizing and some processing of images in real time.

The system consists of a 386-based computer with Imaging Technology digitizing boards. The signal from the analog CCD camera is digitized on the boards and some processing is done in real time; in addition we still record the raw signal on 3/4" video tape for subsequent analysis. The RGB output signal from the system is viewed on a monitor, and then passes through a scan converter where it is converted to either an S-VHS or regular NTSC signal for recording on a Mitsubishi S-VHS Video Recorder. A Polaroid Freeze Frame Camera allows production of hard copy of any RGB image on Polaroid print film or 35 mm print or slide film. Because the image processing techniques which we employ are quite different from those typically used, we have had to do extensive software development. Some of this uses routines which can be run on the boards in real-time, for example, conversion to false color and recursive frame-averaging, but some, for example, computing an image which is the variance of each pixel over time can only be done more slowly off the boards due to the memory requirements. The software, written in C, is now essentially complete. This image processing and software development has been the responsibility of Adrian Ferrier. Adrian began working on this project as an undergraduate with support from the Research Experience for Undergraduates (REU) program. He is now completing this project for his Master's Thesis in our Computer Graphics group at Georgia Tech with a minor in mathematics.

Although laser-induced fluorescence is fairly commonly used for flow visualization it is less often used for quantitative measurements, particularly at the scale we are interested in. Calibration of the system has proven difficult. The beam is expanded from a diameter less than 1 mm by means of three cylindrical lenses to a collimated sheet 430 mm tall. This is substantially larger than employed by most researchers, and this large scale introduces some problems of its own. The laser beam intensity is not uniform over the sheet, and we have been exploiting this non-uniformity to our advantage in being able to illuminate parts of the flow where the dye concentration is higher with less intense light, and those parts where the dye concentration is less with more intense light. In this way, we have been able to expand the dynamic range of the whole image to more than the usual 8-bit (256 parts) range. This also requires careful calibration, however, to obtain the digitized response versus local dye concentration.

We have found it convenient to pass the sheet through a reference cylinder filled with a known dye concentration which is kept within the field of view of the camera. By taking a vertical scan down through the cylinder, we can obtain the laser sheet intensity variation, and correct the image for this variation. Because of the very large magnification of the beam, very slight changes due to mirror drift in the laser result in large changes in the intensity variation. The reference cell allows us to correct for such drifts. Simultaneously, we correct for the lens brightness variation by dividing by an image obtained by photographing a plain, uniformly illuminated target. Because of the large scales imaged, with the beam passing through a longer path length than employed by most researchers, attenuation of the beam cannot be ignored. We have spent considerable effort in calibrating and optimizing the system, and this has proven more difficult than expected, due to the complicated optical setup, trade-offs between camera sensitivity, noise, and filtering of scattered light, among others. We believe that these problems are now resolved, and plan to begin obtaining quantitative measurements shortly.

In addition to flow imaging, we plan to use the laser-induced fluorescence technique to obtain direct measurements of the turbulent flux of tracer, $\overline{u'c'}$. This will be done by simultaneously measuring velocity with an LDA, and tracer concentration by the fluoresced light.

After extensive study, and demonstrations of various systems, we have decided on a system made by Aerometrics, Inc. This will be a fiber-optic system using a backscatter probe which will capture both the scattered light for the LDA measurements and the fluoresced light for the tracer measurements. The fluoresced light is separated from the scattered light and measured by a dedicated PMT which is sampled on receipt of a validated velocity measurement. The advantage of this technique is that the same optical path is used for the LDA and LIF, guaranteeing that the measurements are made simultaneously and at the same point. The signal processor is of the frequency domain type which appear to be much better suited to our application than the traditional counter, tracker, or covariance type processors. Frequency domain processors are more sophisticated than these older types, and behave better in an environment with a low signal-to-noise ratio, such as we are expecting in our stratified flows. We expect delivery of this system around the end of November.

Much work will then be required to get the system operational. We will first try a 25 mm diameter probe fully immersed in the flow, as traversing and refractive index problems are much reduced by this method compared to a larger probe external to the flow. The shorter path length may mean that refractive index matching of the fluids is not necessary, which will simplify the experiments considerably. We will try different optical setups to provide the laser light necessary to excite the fluorescence. The simplest, which will be tried first, is to use the same beams as are used for LDA measurements. If this is not satisfactory, we will go to the light sheet arrangement. The system will then be calibrated by measuring the response to known dye amounts. It will then be used with flow fields in which measurements have been previously reported to compare them with the new technique. Then we will go on to investigate the new flow fields, as outlined in the original proposal.

6-20-91
3+4

Energetics of jet and plume turbulence in stratified fluids
Project Number CBT 8915537

Summary

The purpose of this project is to study the mixing of effluents such as municipal sewage and industrial wastewater discharged into water bodies. These are often from a diffuser which releases the effluent as a jet or plume whose self-induced turbulence causes rapid dilution. If the water body is density stratified, as often occurs in coastal waters, estuaries, and lakes, the stratification can limit the dilution by causing the turbulence to collapse.

We have developed unique optical instrumentation to study such turbulent mixing processes in stratified fluids. We use laser-induced fluorescence in which a sheet of laser light causes dye added to the flow to fluoresce. The light emitted is captured by a CCD camera and digitized. By the use of an image processing technique and careful calibration we can relate the light emitted to local contaminant concentrations, providing much more information on the concentration field than is available by conventional techniques. The instrumentation is used in a towing tank which enables us to simulate a flowing, density-stratified environment. The stratification is obtained by the use of salt and ethanol solutions and is optically homogeneous thus eliminating the refractive index fluctuations which have previously prevented the use of such optical trechniques.

We have used the system to investigate a wide range of flows. The results show much mixing beyond the traditional jet or plume region which is not incorporated into the present generation of mathematical models. Improved techniques for predicting the extent of this mixing and the length of the initial mixing zone have been proposed which should have significant implications for the regulation of discharges and prediction of their environmental impact. Such information will lead to improved mathematical models of mixing and improved design of diffusers for wastewater discharges.

Energetics of jet and plume turbulence in stratified fluids
Project Number CBT 8915537

References resulting from this project:

Ferrier, A. (1991). "Processing Techniques for Flow Images Obtained by Planar Laser-Induced Fluorescence." M.S. Thesis, School of Civil Engineering, Georgia Institute of Technology, Atlanta.

Extensive software development for image processing from the planar laser-induced fluorescence technique for the extraction of quantitative information on tracer concentration fields was reported in this thesis. This software, known as FLIPR, has been made available at no charge to the research community, and is being used at the University of Western Australia, and the Fluid Modeling Facility, U.S. EPA, Research Triangle Park, North Carolina.

Roberts, P.J.W., and Ferrier, A. (1992). "Application of Optical Techniques to the Study of Plumes in Stratified Fluids." Paper 011B-12, AGU Ocean Sciences Meeting, New Orleans, January 27-31.

This invited presentation described the use of our laboratory instrumentation and gave examples of its applications to plume behavior.

Roberts, P.J.W. (1992). "New instrumentation for stratified flow experiments." Fourth Conference on Stably Stratified Flow, Institute of Mathematics and its Applications, Guildford, England, September 21-23.

This invited presentation described new optical techniques for stratified flows, with examples from our laboratory.

Funk, D. (1993). "Application of laser techniques to experimental studies of jets and plumes." M.S. Thesis, School of Civil Engineering, Georgia Institute of Technology, Atlanta.

This thesis was awarded the Sigma Xi Outstanding MS Thesis Award, College of Engineering, 1993. It describes further development of the planar LIF technique, and development and calibration of a specially built combined Laser-Doppler Anemometer - Laser-induced Fluorescence instrument. We now use this instrument for simultaneous measurement of velocity and fluorescence (hence tracer concentration and material fluxes) at a point.

Ferrier, A., Funk, D., and Roberts, P.J.W. (1993). "Application of Optical Techniques to the Study of Plumes in Stratified Fluids." *Dynamics of Atmospheres and Oceans*, 20, 155-183.

This paper describes in detail the use of planar laser induced fluorescence for the study of jets and plumes. It describes the method of calibration for varying dye concentrations and laser power and measurements of beam attenuation through dye fields of varying concentration. The digital corrections of the signal are also described in detail, including corrections for spatial variation in laser sheet intensity, beam attenuation due to absorption, refraction, lens vignetting, time varying and spatial noise, aspect ratio, and camera response. Examples are given of the measurement of various statistics of the concentration fields in horizontal buoyant jets including instantaneous, time average, maxima, minima, standard deviation, and coefficient of variation.

Roberts, P.J.W., Ferrier, A., and Johnson, B.H. (1994). "New Techniques for Experimental Studies of Dredged Material Dispersion." Second International Conference on Dredging and Dredged Material Displacement, Dredging '94. Ed. E. Clark McNair, ASCE, Orlando, FL. Nov 13-16.

This presentation and paper described the application of our instrumentation to studies of the behavior of dredge material plumes in a variety of situations. It described the measurement of tracer concentrations and also extraction of instantaneous and average velocity fields by digital image velocimetry using spatial correlation techniques.

Roberts, P.J.W., Ferrier, A., and Daveiro, G. (1994). "Mixing of Inclined Dense Jets." 47th Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Atlanta, Nov. 20-22.

This presentation described preliminary results of studies on mixing of inclined dense jets.

Roberts, P.J.W., and Ferrier, A. (1995). "Mixing in Inclined Dense Jets," to be submitted the Journal of Hydraulic Engineering, ASCE.

This paper will describe the results of extensive studies on mixing in inclined dense jets, such as occur in industrial wastewater discharges in the ocean and accidental atmospheric gas releases. We report extensive measurements of dilution at the impact point and the increased mixing which occurs in the transition to horizontal flow. The collapse distance is quantified and the flow, which consists of a jet region followed by radial vortex waves, is described.

Ferrier, A. (1995). "Collapse of Plume-Induced Turbulence in Stratified Fluids," PhD Thesis, School of Civil Engineering, Georgia Institute of Technology, Atlanta, presently underway.

This PhD thesis, presently underway, will report use of the LIF and image processing system to study mixing and turbulence collapse of pure plumes in stationary and flowing stratified environments. The studies are being done in the towing tank with linearly stratifications which are refractive index matched. Particular attention will be given to the dynamics of mixing in the flow transition at the terminal rise height and the ultimate turbulence collapse which marks the end of the mixing zone.